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Roldin, Maria Kerstin

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Maria Roldin

DTU Environment
Department of Environmental Engineering

PhD Thesis
October 2012

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Address:	DTU Environment Department of Environmental Engineering Technical University of Denmark Miljoevej, building 113 DK-2800 Kgs. Lyngby Denmark
Phone reception:	+45 4525 1600
Phone library:	+45 4525 1610
Fax:	+45 4593 2850
Homepage:	http://www.env.dtu.dk
E-mail:	reception@env.dtu.dk

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Preface

This thesis is based on research that was carried out during the PhD project "Distributed models coupling soakaways, urban drainage and groundwater" at DTU Environment during the period April 2008-June 2012. The project was carried out under the supervision of Prof. Philip J. Binning (DTU Environment), Assoc. Prof. Peter Steen Mikkelsen (DTU Environment) and Dr. Ole Mark (DHI), as a part of the DSF-funded research project *Black Blue Green – Integrated Infrastructure Planning as Key to Sustainable Urban Drainage Systems (2BG)* and was co-funded by DHI.

Four scientific papers form the base of this thesis:

I. **Roldin, M**., Mark, O., Kuczera, G., Mikkelsen, P.S. and Binning, P.J. (2012). *Representing soakaways in a physically distributed urban drainage model – upscaling invidiual allotments to an aggregated scale*. Journal of Hydrology, 414-415, 530-538.

II. **Roldin, M**., Mark, O., Mikkelsen, P.S. and Binning, P.J. (submitted) *A simplified model for soakaway infiltration interaction with a shallow groundwater table.* Submitted.

III. **Bergman, M**., Hedegaard, M. R., Petersen, M.F., Binning, P., Mark, O. and Mikkelsen, P.S. (2011). *Evaluation of two stormwater infiltration trenches in central Copenhagen after 15 years of operation.* Water Science and Technology 63(10), 2279-2286.

IV. **Roldin, M.**, Fryd, O., Jeppesen, J., Mark, O., Binning, P.J., Mikkelsen, P.S. and Jensen, M.B. (2012). *Modeling the impact of soakaway retrofits on combined sewage overflows in a 3 km2 urban catchment in Copenhagen, Denmark.* Journal of Hydrology, 452-453, 64-75.

Publications made in 2010 and 2011 are in the name of **Maria Bergman**, and publications in 2012 in the name of **Maria Roldin**, due to a change of family name during the PhD study.

The papers are not included in this www-version but can be obtained from the Library at DTU Environment:

Department of Environmental Engineering
Technical University of Denmark
Miljoevej, Building 113
DK-2800 Kgs. Lyngby. Denmark
(library@env.dtu.dk).

The following articles and reports were also prepared during the project but are not included in thesis:

Backhaus, A., **Bergman, M.**, Birch, H., Fryd, O. and Ingvertsen, S.T. 2008. *Sustainable Urban Drainage Systems - 8 case studies from the Netherlands.* Report. Danish Centre for Forest, Landscape & Planning, University of Copenhagen.

Bergman, M., Binning, P., Mikkelsen, P.S. and Mark, O. (2009). *Integrating soakaway infiltration devices in distributed urban drainage models.* The 6th International Water Sensitive Urban Design Conference, Perth, Australia, 5-8 May 2009.

Bergman, M., Binning, P., Kuczera, G., Mikkelsen, P.S. and Mark, O. (2009). *Integrating soakaway infiltration devices in distributed urban drainage models – from allotment to neighbourhood scale.* 8th International Conference on Urban Drainage Modeling, Tokyo, Japan, 7-11 Sep 2009.

Fryd, O., Backhaus, A., Jeppesen, J., Ingvertsen, S.T., Birch, H., **Bergman, M.**, Petersen, T.E.P., Fratini, C. and Jensen, M.B. 2009. *Connected disconnections: Conditions for landscape-based disconnections of stormwater from the Copenhagen sewer system in the catchment area for River Harrestrup.* Report. Danish Centre for Forest, Landscape & Planning, University of Copenhagen.

Fryd, O. , Backhaus, A. , Birch, H., Fratini, C., Ingvertsen, S.T., Jeppesen, J. , Panduro, T.E., **Roldin, M.** , Dam, T.E. , Wenningsted-Torgard, R.M. and Jensen, M.B. (2012). *Potentials and limitations for Water Sensitive Urban Design in Copenhagen: a multidisciplinary case study. Paper presented at the 7th International Conference on Water Sensitive Urban Design*, Melbourne, Australia, 21-23 Feb. 2012.

Kgs. Lyngby, July 2012
Maria Roldin

Acknowledgments

This thesis has a sole author on the cover page, but in reality many people have contributed to the work in one way or another and I would like to say my sincere thank you to all these people.

First and foremost, I would like to thank my three supervisors, Philip Binning, Peter Steen Mikkelsen and Ole Mark. You have with endless patience and a lot of humour guided me on the sometimes complicated path towards a PhD degree, pushed me when I needed it, and supported and encouraged me when I – as all PhD students do from time to time – began to doubt whether I would make it to the end or not. With your knowledge and experience, you have not only contributed greatly to this thesis, but also to my personal and professional development, and I am very grateful to have been under your competent supervision these past years.

Being a PhD student can be a lonesome job sometimes, and therefore I am very grateful to have been a part of the 2BG project team and have had the possibility to collaborate with other PhD students. In particular I would like to thank Ole Fryd, Jan Jeppesen and Marina Bergen Jensen for the successful work with our joint paper and poster – it was a true pleasure working with you. Marina also deserves special thanks for coordinating this big project. To all the other PhD students in the 2BG group – Antje Backhaus, Heidi Birch, Simon Toft Ingvertsen, Chiara Fratini and Toke Emil Panduro Petersen – thanks for all the interesting discussions, fruitful collaboration and support during this time. I have really enjoyed it.

I am also very grateful to George Kuczera, who welcomed me in his research group at the University of Newcastle, Australia, and shared his vast knowledge about hydrologic modeling with me.

During my PhD I spent many hours working with field campaigns, and several people have helped me in this work. Annette Brink-Kjær at Vancenter Syd launched with great enthusiasm a monitoring campaign in Odense and invited me to take part in it. Hanne Kjær Jørgensen, Ulrik Hindsberger and the team at Rørcentret have also been very helpful and obliging by letting me play a part in their field investigations at Teknologisk Institut. For finding, testing and setting up the equipment at Teknologisk Institut, Niels Eisum at DH has been an invaluable help. Mette Fjendbo Petersen and Mathilde Riis Hedegaard have with an impressive commitment engaged in the Nørrebro field campaign and apart from spending numerous hours setting up the equipment and analyzing data, also contributed with valuable modeling work which led to one of the articles in this thesis. To all of you – my sincere thank you!

The PhD project has also involved some programming, and this would never have been possible without considerable and generous assistance from Morten Rungø, Gunvor Tychsen Philip and Jesper Grooss at DHI. I admire your patience with all my beginner's questions about basic programming! Another person who has helped me a lot with knowledge about software, and engaged himself in my project from the very start is Lars-Göran Gustafsson at DHI Sweden. Thank you all!

I am also very grateful for the financial support received, without which this PhD study wouldn't have been possible. The funding has been provided by the Danish council for strategic research (DSF) through the 2BG (Black, blue, green – Integrated infrastructure planning as key to sustainable urban water systems) project, DTU and DHI. Additional funding for conference trips has been given by Otto Mønsteds fund.

Any job would be unbearable without nice colleagues that can share the ups and downs in the everyday working life. To all my office mates and colleagues at DTU Environment and DHI (none mentioned, none forgotten, but you know who you are) I would therefore like to say thank you, for all the pleasant moments, the laughs, the coffee breaks, the chit-chatting and encouraging words along the way.

Last, but not least, I would like to thank my friends and family, and in particular my husband Pontus and my daughter Edith, for always being there for me, helping me through the difficult moments and sharing the joyful moments with me every day. Tack för att ni finns.

Abstract

Alternative methods for stormwater management in urban areas, also called Water Sensitive Urban Design (WSUD) methods, have become increasingly important for the mitigation of urban stormwater management problems such as high runoff volumes, combined sewage overflows, poor water quality in receiving waters, urban flooding etc. WSUD structures are generally small, decentralized systems intended to manage stormwater near the source. Many of these alternative techniques are based on infiltration which can affect both the urban sewer system and urban groundwater levels if widely implemented. In order to assess these effects at local- and catchment-scale, there is a need for reliable and efficient modeling tools that can account for the interaction between the various urban water systems involved.

This thesis focuses on small-scale stormwater infiltration structures, often called soakaways, and how these can be modeled in an integrated environment with distributed urban drainage and groundwater flow models. The thesis:

1. Identifies appropriate models of soakaways for use in an integrated and distributed urban water and groundwater modeling system
2. Develops a modeling concept that is able to manage the bi-directional interaction between stormwater infiltration and groundwater
3. Develops suitable upscaling/downscaling techniques for the integrated soakaway model
4. Assesses the effects of extensive use of soakaways on sewer and groundwater flows in case studies

Based on a review of the literature and on modeling studies, a new modeling concept is proposed which fulfills the need for integrated models coupling distributed urban drainage with groundwater. The suggested solution consists of a base equation for soakaway infiltration and additional components for clogging, upscaling/aggregation and groundwater interaction. The soakaway infiltration model consists of a mass balance equation for the soakaway with a depth dependent term for outflow that is based on the Darcy equation. Clogging is accounted for by modifying the hydraulic conductivity to account for low conductivity sediments deposited in the bottom of the soakaway. Upscaling considers variation in soil properties and it is shown that an upscaled geometric

mean conductivity best matches a spatially variable model. Finally, the decrease in soakaway infiltration due to groundwater table rise is accounted for using an analytical expression for the local mounding under the soakaway.

These components can be combined to create a model that is best suited to the desired application. The model is tested on a case study in Harrestrup Å, Copenhagen where it is shown that in areas with high groundwater tables and low permeability soils, soakaways provide only a modest reduction of peak stormwater loads to the sewer system. The case study shows that soakaways will work best in areas with deeper groundwater and more permeable soils.

The soakaway modeling system developed in this thesis provides a simple, but complete description of soakaway behavior. The next step is to include it in commercial software and benchmark it for a broad range of case studies.

Dansk samenfatning

Alternative metoder for håndtering af regnvand i byer, såkaldte LAR (Lokal afledning af regnvand) løsninger, er blevet et populært alternativ til trationelle kloakløsninger for at håndtere problemer som f.eks. overløb fra fælleskloakerede områder, dårlig vandkvalitet i vandløb og søer og oversvømmelser. LAR-strukturer er generelt små, decentraliserede systemer der håndterer regnvandet tæt på kilden. Mange af disse alternative teknikker er baserede på infiltration af regnvand, hvilket kan føre til betydelige effekter på kloaksystemet og det urbane grundvandssystem, hvis de bruges i stor udstrækning. For at kunne vurdere effekten på både den lille skala og på et helt opland er der brug for pålidelige og effektive modelværktøjer, der kan beskrive interaktionen mellem de forskellige dele af det urbane vandsystem, der er involverede.

Denne afhandling fokuserer på småskala infiltrationssystemer for regnvand, også kaldet faskiner, og hvordan disse kan modelleres i et integreret miljø med distribuerede modeller for afløbssyemer og grundvandsstrømning. Formålene er at:

1. Identificere passende modeltyper for faskiner, der kan bruges i et integreret miljø med distribuerede modeller.
2. Udvikle et modelkoncept, der kan håndtere interaktionen mellem infiltration og grundvand.
3. Udvikle passende opskalerings- og nedskaleringsmetoder for den integrerede faskinemodel.
4. Vurdere effekten af omfattende brug af faskiner på kloaksystemer og grundvandsstrømning i konkrete eksempler.

Baseret på en litteraturgennemgang og på modelstudier præsenteres et forslag til et nyt modelkoncept, der opfylder alle krav for at kunne bruges i et integreret miljø med distribuerede modeller. Den foreslåede løsning består af en grundligning for infiltration fra faskiner og supplerende modelkomponenter for tilstopning, opskalering/aggregering og grundvandsinteraktion. Grundligningen består af en massebalance for faskinen, med en nedsivningsterm baseret på Darcy's ligning og afhængig af vanddybden i faskinen. Tilstopning modelleres gennem en reduceret hydraulisk ledningsevne relateret til et ekstra lag af sediment med lav konduktivitet på bunden af faskinen. Opskaleringsmodellen tager hensyn til variation af jordparametre, og der vises at en opskalering hvor den geometriske middelværdi af konduktiviteten bedst svarer til en spatialt distribueret model. Lavere infiltration på grund af stigning af grundvandsstanden beregnes vha. en analytisk ligning for den lokale forhøjning under faskinen.

Disse komponenter kan kombineres for at skabe en model alt efter behov, afhængigt af den specifikke opgave. Modellen er afprøvet i et case studie ved Harrestrup Å, København, hvor der vises at i områder med høj grundvandsstand og lav konduktivitet i jorden, leder faskiner kun til en begrænset nedsættelse af regnvandsmængder til afløbsstystemet. Case studiet viser også at faskiner vil virke bedst i områder med dybere grundvandsstand og mere gennemtrængelige jordtyper.

Den foreslåede model udgør en enkel, men komplet beskrivelse af faskiners dynamik. Næste trin er at inkludere modellen i kommercielle computerprogrammer, og afprøve den i et bredt udvalg af forskellige case studier.

Table of contents

List of symbols

Symbol	Description	Unit
c	Fitting parameter for clogging model	m^{-1}
Δh	Distance between soakaway bottom and groundwater mound	m
h	Water depth in soakaway	m
$K_{fs,0}$	Field-saturated hydraulic conductivity for non-clogged conditions	m/s
$K_{fs,clogged}$	Field-saturated hydraulic conductivity for clogged conditions	m/s
$K_{fs,effective}$	Effective field-saturated hydraulic conductivity for multiple soakaways	m/s
$K_{fs,horizontal}$	Horizontal field-saturated hydraulic conductivity	m/s
$K_{fs,vertical}$	Vertical field-saturated hydraulic conductivity	m/s
L	Soakaway length	m
n	Number of soakaways	-
$q_{horizontal}$	Horizontal infiltration rate per m^2 wetted soakaway area	m/s
$q_{vertical}$	Vertical infiltration rate per m^2 wetted soakaway area	m/s
Q_{in}	Inflow rate to soakaway	m^3/s
Q_{inf}	Infiltration rate from soakaway to soil	m^3/s
$Q_{inf,0}$	Infiltration rate without groundwater influence	m^3/s
$Q_{inf,grw}$	Infiltration rate under groundwater influence	m^3/s
Q_{of}	Overflow rate from soakaway to sewer	m^3/s
θ	Volumetric soil moisture content	-
θ_i	Initial soil moisture content at soakaway bottom	-
θ_s	Saturated soil moisture content	-
V	Volume of water in soakaway	-
W	Width of soakaway	-

1. Introduction

Stormwater in urban areas can be managed in various ways. Traditional stormwater management systems are usually designed to remove the water as quickly as possible from the urban catchment, either through a combined sewer system where it is mixed with sewage water and led to a wastewater treatment plant, or through a separate system where it is diverted to a nearby water body. In the past decades, alternative and more decentralized methods have been developed which all, in one way or another, attempt to shift the urban hydrologic cycle back towards a more natural state (Revitt et al., 2003; Chocat et al., 2007; Elliott and Trowsdale, 2007). These methods are often referred to as *Water Sensitive Urban Design (WSUD)* systems[1].

WSUD has become an important topic in Denmark in recent years, where alternative methods are needed to manage the higher stormwater load that is a result of increased urbanization and more frequent extreme rainfall events induced by climate change. The official climate adaptation plan of the city of Copenhagen emphasizes the need for local stormwater management, and the city also provides economic incentives for citizens who construct soakaways to allow stormwater infiltration on their private properties (City of Copenhagen, 2012). Research on WSUD systems, including stormwater infiltration is therefore required to address this societal need.

1.1 Systems for stormwater infiltration

Stormwater infiltration systems is a wide term that covers many different techniques. This thesis is focused on the small-scale infiltration systems that are often referred to as *soakaways* (the term *infiltration trenches* is also commonly found, e.g. Warnaars et al., 1999 or Revitt et al., 2003).

A soakaway is an underground cavity filled with a porous material connected to an inlet where surface runoff from e.g. roofs and other impervious areas can enter. Its main function is retention of stormwater due to infiltration into the ground and storage (BRE, 1991). Soakaways are traditionally found in house gardens and alongside roads, where they receive runoff from impermeable areas

[1] Alternative terms are *stormwater best management systems (BMPs)*, *sustainable urban drainage systems (SUDS)*, *Low Impact Development (LID)* and *Green Infrastructure (GI)*. In Denmark, the generally accepted term is *Lokal afledning af regnvand (LAR)*.

like roofs and roads. They are generally long and narrow, and the filling material is usually either gravel or plastic cassettes (ibid.). They can be equipped with an overflow pipe to the sewer to reduce the risk of local flooding during heavy rainfall events. Soakaways are particularly common in the UK (Revitt et al., 2003), and have also become increasingly popular in Denmark in recent years.

Figure 1 shows a sketch of a typical soakaway setup.

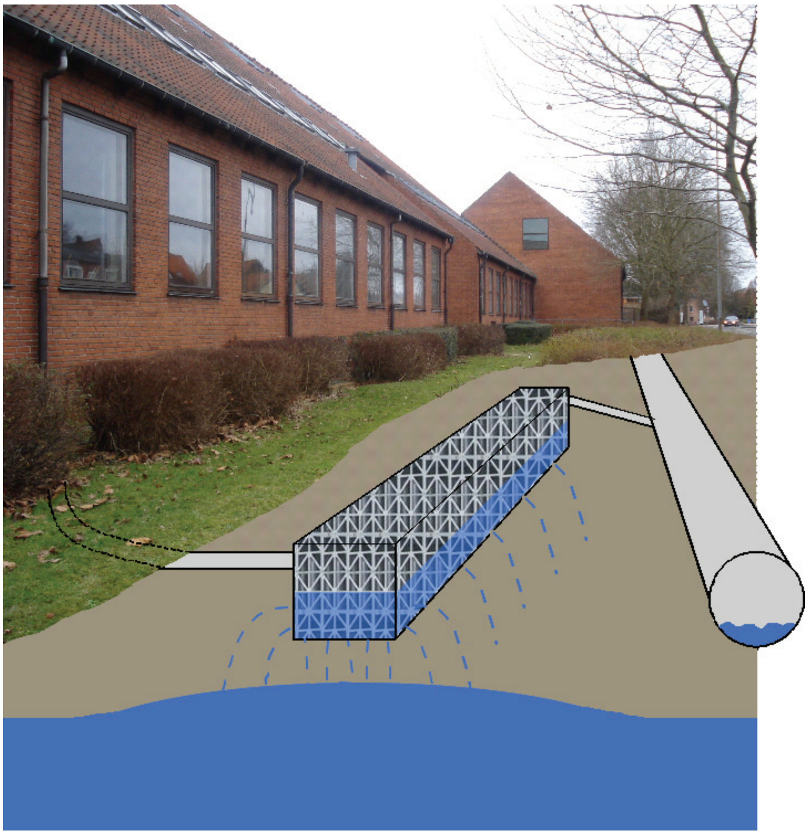

Figure 1. Schematic setup of a soakaway collecting stormwater from the roof of Risingskolen, Odense. Inlet pipe to the left, soakaway in the middle and overflow pipe and sewer to the right.

The performance of a soakaway depends mainly on the geometry and dimensions of the soakaway and the properties of the surrounding soil (Mikkelsen, 1995; Freni et al., 2009). The latter include parameters such as soil type, saturated hydraulic conductivity and soil moisture content. In addition, it is widely known that soakaway performance tends to deteriorate with time, as fine particles entering the soakaway with the stormwater runoff will settle at the base of the soakaway and reduce the infiltration through the bottom area (Warnaars et al., 1999; Revitt et al., 2003; CIRIA, 2007; Siriwardene et al., 2007; Endo et al., 2009; etc.)

1.2 Why infiltrate stormwater?

There are several well documented drawbacks related to traditional stormwater management. Pipe-based systems in combination with increasing urbanization and growing impermeable areas, lead to increased runoff velocity, high runoff volumes and have a negative effect on the water quality in receiving waters (Dietz, 2007). In combined systems, where stormwater and wastewater are mixed, the addition of stormwater flows during wet weather leads to large variations in inflow to the wastewater treatment plants. For heavy rainfall events when the sewer network becomes overloaded, a mixture of wastewater and stormwater is typically discharged without treatment to nearby water bodies (combined sewage overflows – CSOs) which can lead to deterioration of the chemical and ecological status of the recipient (Chocat et al., 2007).

Infiltration of stormwater can also contribute to enhanced recharge of groundwater and increased baseflow in streams, which may be beneficial in arid regions and in areas where the baseflow is low (Dillon, 2005).

Small-scale stormwater infiltration systems like soakaways manage the stormwater near the source, and can thereby contribute to reducing the runoff volumes, slowing down runoff volumes, and enhancing groundwater recharge and baseflow. For this reason, they have become increasingly popular in the past decades for mitigating the effects of urbanization on the urban water systems (Revitt et al., 2003; Chocat et al., 2007).

1.3 Why model stormwater infiltration?

Stormwater infiltration has a direct effect on the urban drainage (sewer) flows as well as the urban groundwater system. Indirectly it may also affect surface waters in the urban environment such as stream flows or street flooding. The effects vary with several parameters, e.g. rainfall characteristics, geology, type and design of infiltration structure, etc. Infiltration is furthermore a complex process, affected by factors like soil type, soil moisture content, groundwater table location among other factors. To be able to predict the behavior of these systems, and to promote and facilitate the use of small-scale stormwater infiltration systems and other types of WSUD techniques, accurate and accepted models are essential (Dietz, 2007).

1.4 The challenge in modeling stormwater infiltration systems

Several challenges in the modeling of WSUD, including stormwater infiltration systems, have been identified in recent literature reviews. WSUD techniques interact with several urban water systems (urban drainage, urban ground water, urban surface waters, etc.) and therefore require a more integrated modeling approach, where the whole urban water cycle is considered (Schmitt and Huber, 2006). The groundwater representation and integration with receiving waters in current state-of-the-art models of urban drainage and water sensitive urban design, often inadequately describes WSUD techniques (Elliott and Trowsdale, 2007). Furthermore, due to the heterogeneity in temporal and spatial scales and the complexity of the urban water system, an efficient and adequate IT framework as well as harmonized model interfaces are needed to facilitate the integration and linkage between existing models of various sub-systems in the urban water cycle (Schmitt and Huber, 2006). There is also a need for investigation and improvement of methods for spatial and temporal aggregation of these usually small-scale and decentralized systems (Elliott and Trowsdale, 2007).

Whilst upscaling and aggregation of hydrological and geological parameters has been a field of research in groundwater flow since the 1960s (see for instance Matheron, 1967), very little research exists on upscaling of infiltration-based WSUD systems with distributed parameters in an integrated environment, where the infiltration systems affect and are affected by rainfall-runoff processes, pipe flow in the urban drainage network, local groundwater conditions etc. Similarly, the downscaling of groundwater models to be able to accurately represent local effects from small-scale infiltration systems is an issue that will become relevant if the effects of stormwater infiltration systems are to be assessed on a large scale.

1.5 Aims and objectives

The aim of this PhD study was to develop an integrated and distributed modeling concept for soakaways and similar small-scale stormwater infiltration systems, that can be used to assess the quantitative effects of such systems on groundwater and urban drainage flows at a multi-scale level. This included analyzing the potential for extensive use of soakaways, and its effects on sewer flows, including combined sewer overflows, and groundwater response and interaction.

The PhD study had the following objectives:

1. Identify appropriate model types for soakaways to use in an integrated environment with distributed models
2. Develop a modeling concept able to manage the bi-directional interaction between stormwater infiltration and groundwater
3. Develop suitable upscaling/downscaling techniques for the integrated soakaway model
4. Assess the effects of extensive use of soakaways on sewer and groundwater flows in case studies

The scope was limited to water quantity modeling, i.e. qualitative aspects of soakaway infiltration are not included.

The purpose of this thesis is to present and evaluate the new modeling concept developed during the PhD study, and relate this to the challenges and gaps in current state-of-the-art models of soakaways coupled to distributed urban drainage and groundwater flow models.

1.6 Thesis structure

In chapter 2, the state-of-the-art in soakaway modeling is described. The models are described and their differences highlighted so as to inform the selection of an appropriate model type for any specific purpose. This chapter is linked to the first objective presented above.

Chapter 3 summarizes modeling of soakaways in distributed urban drainage models and the specific challenges that are related to this. Suitable model types of small-scale infiltration systems are presented, based on the aspects listed in chapter 2, and examples of recommended upscaling and aggregation techniques are given. Chapter 3 is linked to the third and fourth objectives listed above.

Chapter 4 considers how soakaway models can be coupled to a distributed groundwater model, focusing on how to handle the bi-directional interaction between infiltration and groundwater, and how to account for local groundwater mounding. This chapter addresses the second and third objectives.

In chapter 5, the experiences gained from practical applications of the suggested model are discussed and the proposed solution is compared with other similar approaches. Potential future applications and model developments are also discussed.

Chapter 6 contains overall conclusions and specifically relates these to the aims and objectives. Recommendations for future research, based on the discussion and conclusions, are presented in chapter 7.

2. General aspects on soakaway modeling

A variety of models of stormwater infiltration systems are available and have been developed for different purposes. The mass balance for the soakaway (Equation 1) is however generally consistent for all models.

$$\frac{dV}{dt} = Q_{in} - Q_{inf} - Q_{of} \qquad \text{Equation 1}$$

The biggest difference between models and the main modeling challenge lies in how the infiltration rate (Q_{inf}) is modeled. The following section outlines the main aspects that vary between different soakaway infiltration models and which need to be considered when choosing an appropriate model type.

2.1 Model complexity

The simplest models assume that there is a constant infiltration rate out of the soakaway as long as there is water in it. This approach is commonly found in older dimensioning guidelines (IDA, 1994). A more accurate, but still very simple approach, is to model the infiltration rate as a linear function of the wetted area or water depth (Stahre and Urbonas, 1990; Mikkelsen, 1995, **Roldin et al., 2012 - Paper I**). This modeling approach is originally based on Darcy's law (Darcy, 1856) in combination with the assumptions that the infiltration from a soakaway is gravity driven, that flow conditions are close to saturated, and that the flow cross-sectional area is equal to the wetted area of the soakaway (see Figure 2).

At the other end of the simple-complex scale are 2D or 3D models of soakaways where the infiltration of water is modeled by Richards' equation (Richards, 1931), a non-linear partial differential equation describing water movement in unsaturated porous material like soils. (e.g. Duchene et al., 1994, Korkmaz and Önder 2006, **Roldin et al., 2012 - Paper II**). This kind of model requires the identification of soil moisture retention parameters and estimates of initial moisture content in the soil, and numerical solutions are necessary. Figure 3 shows an example.

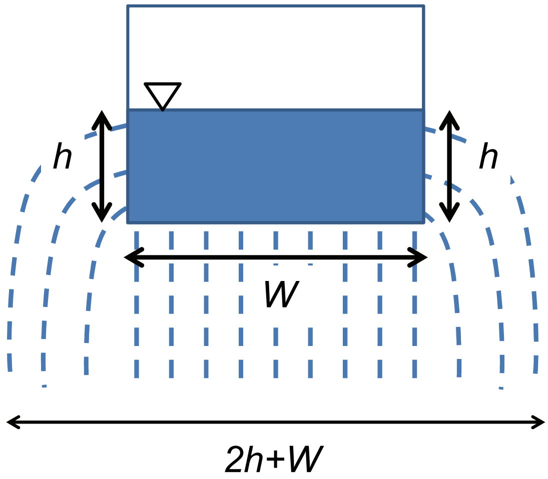

Figure 2. Conceptual illustration of assumed flow pattern around a soakaway in a simple soakaway model

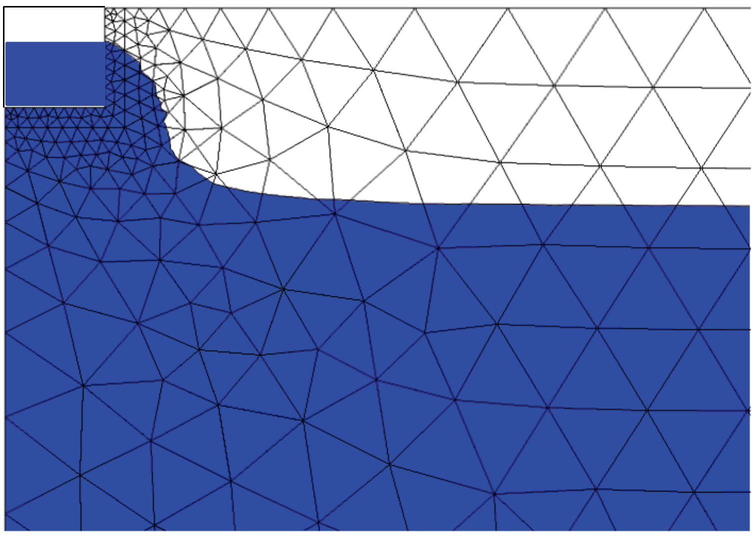

Figure 3. Example figure of a 2D soakaway model with a finite element grid. From **Roldin et al. (2012 – Paper II)**. The square in the top left corner represents the soakaway, the gridded area is the soil domain and blue shaded area is the saturated part of the soil.

In between these two extremes there are a number of alternative models. Many of them are based on either Richards equation (e.g. Browne et al., 2008), the Green-Ampt equation (Green and Ampt, 1911) (e.g. Freni et al., 2009) or an exponential decay model similar to Horton's infiltration model (Horton, 1933) (e.g. Papa and Adams, 2005).

Complex soakaway models are commonly used to analyze individual soakaways, either in the field or in a lab experiment (Browne et al., 2008), or to provide estimates of interaction effects with a shallow groundwater table (Guo, 1998; **Roldin et al., 2012 – Paper II;** etc. They are also used to calibrate, validate and evaluate more simple models, as a complement to, or a substitute for, measurements on a real system (e.g. Duchene et al., 1994; **Roldin et al., 2012 – Paper II**). The advantages of complex models are that they are able to take a number of factors into account, such as initial moisture content, specific soil properties and soakaway geometries, etc. Hence they are able to provide very accurate predictions for various conditions.

The advantages of the simple soakaway models are that they require a lot less input data, and they are thus suitable to use in situations where the input parameters used in the more complex models (e.g. soil moisture retention parameters) are not readily available. In addition they require much less computational effort than e.g. a 2D model, which makes them well suited for use in multiple soakaway modeling at larger scales (e.g. **Roldin et al., 2012 – Paper IV**).

2.2 Infiltration flow pattern in the unsaturated zone

Some models only account for infiltration from the sides (IDA, 1994; BRE, 1991), since the bottom of the soakaway is assumed to clog with fine particles and become close to impermeable. This clogging effect on soakaways has been shown in numerous studies (e.g. Lindsey et al., 1992; Deschene et al., 2004; Siriwardene et al., 2007; Endo et al., 2009; **Bergman et al., 2011 – Paper III**). Other models however do the opposite and assume that all infiltration occurs through the bottom, based on the general flow direction in unsaturated soils, which is downwards (Papa and Adams, 2005). Some infiltration models, like the Green-Ampt model, are strictly one-dimensional and need to be modified if infiltration from the sides is to be accounted for (e.g. Freni et al., 2009).

The different modeling approaches related to flow direction are illustrated in figure 4.

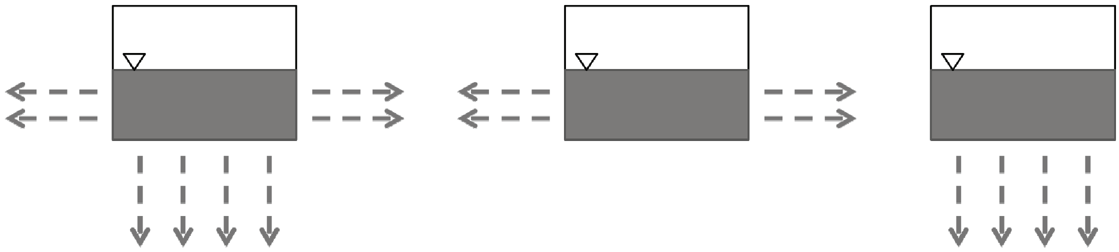

Figure 4. Different soakaway modeling approaches: infiltration from the entire wetted area (left), infiltration only from the sides due to clogging (middle) and infiltration only from bottom based on the general flow direction in unsaturated soils (right).

2.3 Spatial scale and resolution

Soakaways are usually small-scale stormwater structures, with length scales of order 10 m. The appropriate spatial scale and resolution of a soakaway model will depend on the use and purpose of the modeling study. Complex, 2D soakaway models based on Richard's equation require small element sizes in the numerical grid or mesh (in the order of centimeters) to achieve accurate solutions (e.g. Celia and Binning, 1992).

Multiple soakaway modeling in large catchments adds another constraint: 2D models may quickly become unrealistic in large catchments due to the high computational effort required. It may even be infeasible to model soakaways as individual units, and they must then be aggregated into larger units or clusters. Aggregation and upscaling processes will however introduce extra uncertainty to the model (Heuvelink and Pebesma, 1999), and the advantages and disadvantages of upscaling must therefore be carefully considered for each specific case, for instance as demonstrated by Finke et al. (2002).

Multiple soakaway modeling also requires attention to possible interaction effects between individual soakaways, such as interconnected mounds and subsurface flow between soakaways (Antia, 2008).

2.4 Temporal scale and resolution

If a soakaway model is to be used in long-term simulations (years to decades) it needs to be able to account for clogging effects. Several suggestions on how this can be modeled have been reported in literature. Some models are empirical time-dependent (Deschene et al., 2004; Endo et al., 2009), but a physically based time-dependent clogging model has also been proposed (**Bergman et al., 2011 –**

Paper III). Other models relate the infiltration rate to the accumulated mass of particles (Siriwardene et al., 2007; Freni et al., 2009). The models that are functions of accumulated sediment mass require knowledge about particle concentration in the stormwater, whereas the time-dependent models all rely on calibration to estimate one or more parameters. The advantage of the physically based time-dependent clogging model is that its unknown parameters are related to physical parameters such as clogging layer thickness and initial saturated hydraulic conductivity, and these are more easily estimated than the parameters of empirical models.

Temporal resolution – the time step length – of a soakaway model is dependent of the model complexity and spatial resolution. Infiltration models based on Richards' equation with a high spatial resolution may require very small time steps in some periods (in the order of a second), if the head gradients in the unsaturated zone are high (see e.g. Celia and Binning, 1992). Models with low complexity and slow infiltration rate may be run with time steps of 1 hour or greater (**Roldin et al., 2012 – Paper II**).

2.5 Integration with other models

Integrated models refer to models that are designed to be a part of (or are communicating with) a larger model system, such as an urban drainage model or a local or regional groundwater model (Schmitt and Huber, 2006). Examples of stormwater drainage models that incorporate various WSUD techniques can be found in Elliott and Trowsdale (2007). Some examples are also found where these techniques are incorporated in groundwater models, see for instance Jeppesen (2010).

Information exchange between models can either be sequential (one model is run first, then another) or bi-directional (all models run at simultaneously, exchanging data during runtime) (Schmitt and Huber, 2006). As an example, urban drainage models with a rainfall-runoff model and a pipe flow model are often run sequentially, first the rainfall-runoff model, then the pipe flow model (DHI, 2011a). Figure 5 shows a conceptual illustration of sequential and bi-directional simulations.

Bi-directional integrated models add additional restrictions on the model type, spatial and temporal resolution and scales, and type of input and output needed.

Soakaway models need to be programmed in a language and environment that is compliant with the other models, or already integrated in the modeling software (Schmitt and Huber, 2006). There is ongoing work to overcome these difficulties, for instance by creating the programming standard OpenMI (Gregersen et al., 2007).

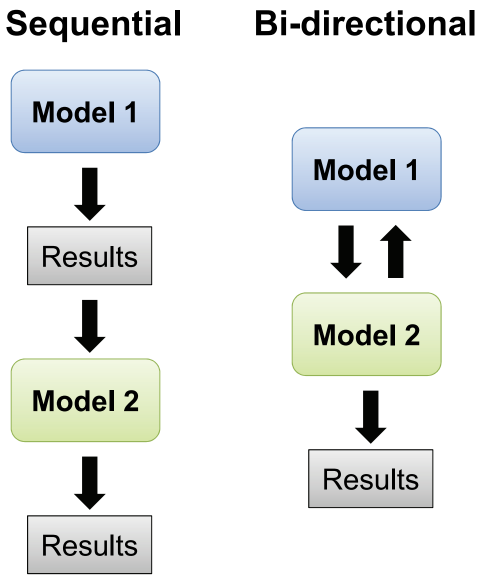

Figure 5. Conceptual illustration of sequential vs. bi-directional modeling

Standalone soakaway models refer to models where the soakaways are modeled as individual units with little interference with other systems. A common setup is a single soakaway in a soil matrix with well defined parameters and no interference with groundwater, or a fixed groundwater table (Duchene et al., 1994; Guo, 1998; Browne et al., 2008; etc.). The water depth in the soakaway is either set to be constant or determined by an inflow hydrograph and the resulting infiltration rate. Since they are run independently of other models there are few requirements regarding programming language and style, temporal and spatial scale, type of input and output data etc. and they thus allow for a large freedom of choice for the model developer and users.

3. Modeling soakaways in distributed urban drainage models

The term *distributed urban drainage models* here refers to deterministic models of urban drainage systems, represented by a network of pipes and joints in a coordinate system. They are driven by rainfall input data, which are converted to runoff by a *rainfall-runoff model*, and the runoff then provides input to the *pipe flow model* that calculates the flow in the sewer network. (For examples, see Mark and Hosner, 2004 or Rossman, 2008).

Figure 6 shows a conceptual illustration of a distributed urban drainage model.

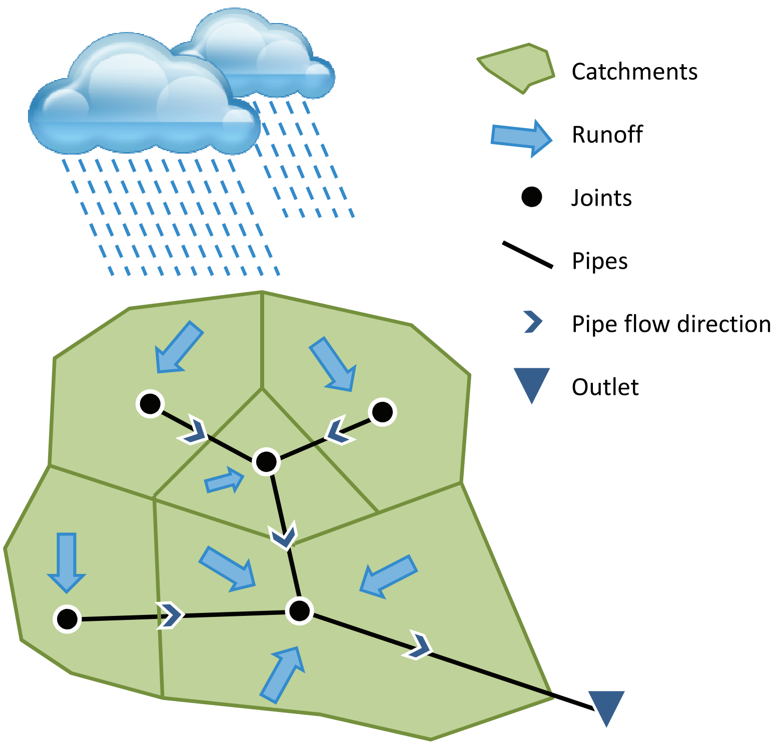

Figure 6. Conceptual illustration of a distributed urban drainage model with catchments and a pipe network.

In the following sections, the coupling of soakaway models to a distributed urban drainage models and the issues raised in chapter 2 are discussed. The chapter is concluded with a suggested model solution and an example from an applied context.

3.1 Model complexity

The complexity of distributed urban drainage models is often related to the spatial scale they are modeled on. Many models cover large catchments (several hectares) and contain hundreds or thousands of pipe and joint elements (for examples see Figure 7 and e.g. Elliot et al., 2010; **Roldin et al., 2012 – Paper IV**; Semadeni-Davies et al., 2005; Peters et al., 2007; etc). From this perspective, simple soakaway models are preferred over more complex ones, since they require less computational effort and so can be integrated with complex urban models without an unreasonable increase in computational cost.

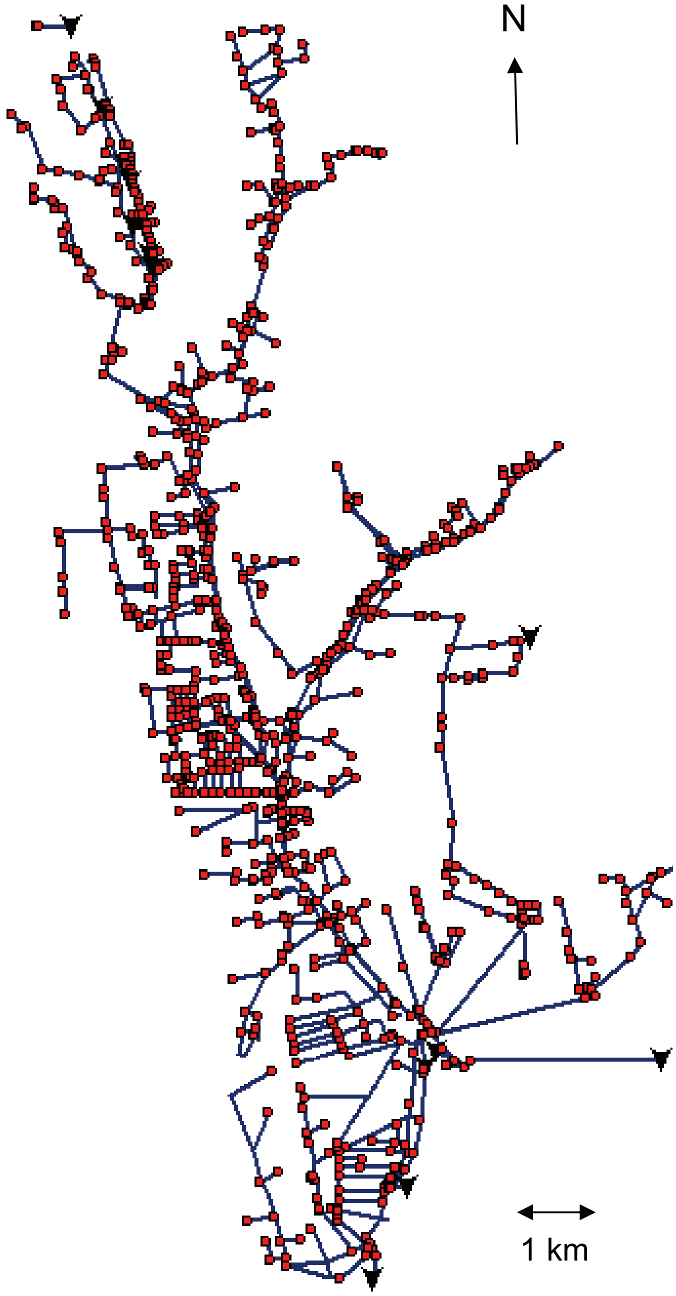

Figure 7. Distributed urban drainage model for the Damhus river wastewater treatment plant catchment. From **Roldin et al. (2012 – Paper IV)**

Another reason for choosing a simple soakaway model is that detailed and distributed soil data is often scarce (e.g. **Roldin et al., 2012 – Paper IV**) and the spatial variability and uncertainty of soil parameters such as the saturated hydraulic conductivity can be very large (see for instance Warnaars et al., 1999). This uncertainty and lack of data is likely to have more impact on the results than the error resulting from using a simple model instead of a more complex one (Jeppesen, 2010; **Roldin et al., 2012 – Paper I and Paper II**)

3.2 Infiltration flow pattern in the unsaturated zone

The Green-Ampt infiltration model, which assumes only vertical infiltration, is a well-known and widely used method for determining infiltration of rainfall, frequently also used in urban drainage modeling (e.g Smith, 1993; Tsihrintzis and Hamid, 1998). However, soakaway infiltration depends a lot on geometry (Mikkelsen, 1995) and thus a conventional 1D infiltration model is often not appropriate to describe this process. Modified versions of the Green-Ampt function have, however, been shown to work well with some calibration effort (Freni et al., 2009).

A large number of modeling and field studies on standalone soakaways show that infiltration from a soakaway occurs both through the bottom and the sides, albeit at a different rate (Duchene et al., 1994; Mikkelsen, 1995; Warnaars et al., 1999; **Bergman et al., 2011 – Paper III**, etc.). Table 1 shows examples of estimated horizontal and vertical infiltration rates from three different studies.

Table 1. Examples of estimated (measured or modeled) infiltration rates from various studies. The modeled results are based on 2-dimensional solutions of Richards' equation.

Study	Type	$q_{horizontal}$	$q_{vertical}$	unit
Duchene et al., 1994*	Modeled	18.5	26.9	µm/s
Warnaars et al., 1999	Measured	0.89	0.28	µm/s
Bergman et al., 2011 – Paper III	Measured	0.29	0.075	µm/s

* The selected example refers to the infiltration rate in a loamy soil with 3 m to the groundwater table, after 2h of simulation. Results from several other scenarios can be found in the original article.

The above data indicates that a soakaway model should preferably include both horizontal and vertical infiltration, and be able to distinguish between horizontal and vertical infiltration rates when used with distributed urban drainage models.

3.3 Spatial scale and resolution

Many distributed urban drainage models are developed at a scale greater than that of individual allotments (see e.g. **Roldin et al., 2012 – Paper IV** and Figure 7), since they cover large catchments where representation of each individual allotment would be impractical. Soakaways, on the other hand, are typically small-scale structures draining the stormwater from single properties. Thus, some kind of upscaling or aggregation method is often necessary when modeling soakaways in distributed urban drainage models. Figure 8 shows an example of aggregation of a distributed urban drainage model with soakaway elements.

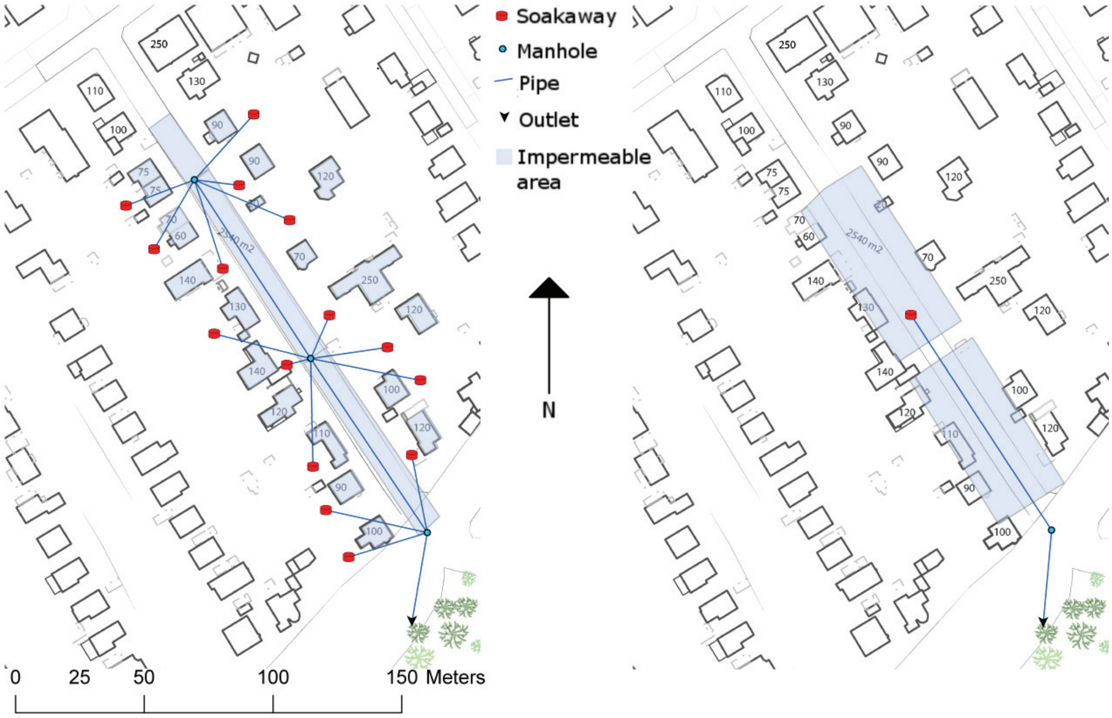

Figure 8. Example of a distributed urban drainage model set up at different spatial scales – individual allotment scale (left) vs. aggregated scale (right). From **Roldin et al. (2012 – Paper I)**.

Specific upscaling methods have been reported in literature, for instance regression curves for stormwater infiltration systems at different spatial scales (Kronaveter et al., 2001) or the re-use of computation results on allotment scale for devices with similar properties in a model for decentralized urban water systems (Hardy et al., 2005). On-site stormwater control devices with similar properties can successfully be aggregated unless the aggregation is very coarse (Elliott et al., 2010). However, if the properties (e.g. the hydraulic conductivity) vary between individual soakaways, attention must be paid to aggregation methods and averaging of these parameters. **Roldin et al. (2012 – Paper I)** showed that weighted geometric mean is a suitable averaging method for the saturated hydraulic conductivity parameter provided that it can be described as being log-normally distributed. The same study showed that the errors resulting from aggregation were small compared to other uncertainties, and that overflow volumes from soakaways were better represented than peak overflow rates in the aggregated model (ibid.).

3.4 Temporal scale and resolution

Soakaways have a relatively slow response time to rainfall compared to pipe networks. The infiltration from a soakaway can usually be modeled with a time steps of minutes to hours (**Roldin et al., 2012 – Paper II**) whereas pipe flow models may require time steps of a few seconds (Elliott and Trowsdale, 2007). When integrating soakaway models with urban drainage pipe flow models, it is thus possible – but not necessary – to use the same temporal resolution for the soakaway model as the urban drainage model. A special case is when the urban drainage models run in discontinuous mode, i.e. when only wet-weather periods are simulated (e.g. Jakobsen et al., 2001). In these simulations, where the time step between wet-weather periods can be several days or weeks long, each period is usually initiated with an empty pipe system or a specified initial condition, independent of the conditions at the end of the previous wet-weather period. Since a soakaway can take weeks to empty, each new wet-weather period is likely to be influenced by the previous one, and thus specific attention should be paid to the initial conditions of soakaways in each new simulation period.

Clogging effects are important to consider when simulating long periods in an urban drainage system, since clogged soakaways are more likely to overflow and thereby affect the urban drainage flows. The effect of clogging on the number of overflows has been investigated for a soakaway system in central Copenhagen (**Bergman et al., 2011 – Paper III**). This study used a physically based clogging model combined with a soakaway infiltration and mass balance model to predict the future behavior of the soakaway system and its effects on sewer flows. Figure 9 shows the current and predicted overflow volumes and frequency calculated in this study.

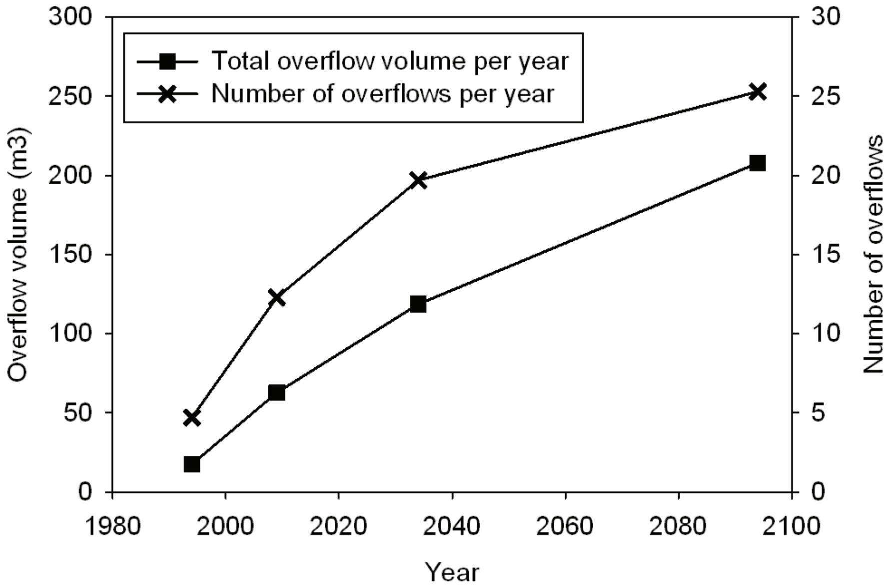

Figure 9. Current and predicted overflow volume and frequency from a soakaway system in central Copenhagen. From **Bergman et al. (2011 – Paper III)**.

3.5 Integration with urban drainage models

Soakaways without an overflow are not directly linked to the sewer system and therefore only considered in the rainfall-runoff model. A simple and commonly found method for this is to simply reduce the impervious area in the catchment where the soakaways are located (e.g. Semadeni-Davies et al., 2008, **Roldin et al., 2012 – Paper IV**). Soakaways that have an overflow structure to the sewer are hydraulically linked to the sewer system. They can then either be modeled as a part of the rainfall-runoff model, or as a part of the pipe flow model, and in existing models of various WSUD techniques both types of integration are found depending on the type of device and the urban drainage model (Elliott and Trowsdale, 2007). When soakaway models are only part of the rainfall-runoff model, runoff results can be used for sewer modeling, but the interaction is one-directional, i.e. soakaway behavior affects the sewer flows but not vice versa. If the soakaway model is part of the pipe flow model, possible interactions like backwater effects, risk of backflow of water from sewer to soakaways etc., can be more accurately determined (**Roldin et al., 2012 – Paper I and Paper IV**).

The integration in **Roldin et al. (2012 – Paper I and Paper IV)** is based on a built-in function for user-written control in the distributed urban drainage model (DHI, 2011a). This allows the soakaway and pipe flow models to exchange information during runtime. Overflow from the soakaway to the sewers is calculated by the pipe flow model based on the water level in the soakaway and the downstream water level.

3.6 Suggested solutions

This chapter shows that if a soakaway model is to be integrated with a distributed urban drainage model, then it should preferably fulfill the following criteria:

- Be relatively simple and require little computational effort
- Be able to account for infiltration both through sides and bottom of the soakaway and distinguish between infiltration rates of these
- Include an upscaling or aggregation method that does not introduce large errors in the output and is able to handle averaging of distributed parameters
- Include an optional clogging model that can be used if long periods are simulated.
- Include an analytical solution to estimate the performance during dry periods, to facilitate use together with urban drainage models run in discontinuous mode.
- Be possible to integrate either as part of a rainfall-runoff model or a pipe flow model depending on whether the soakaway is linked to the sewer system or not.

The model of **Roldin et al. (2012 – paper I)** fulfills the first two criteria, and has been shown to represent soakaway dynamics sufficiently well. Their model describes the soakaway using:

$$Q_{inf} = K_{fs,sides} \cdot 2h(L+W) - K_{fs,bottom} \cdot LW \qquad \text{Eq.2}$$

K_{fs} is the field-saturated hydraulic conductivity and Q_{inf} is part of the mass balance in equation 1. If the soakaway model is integrated in a pipe flow model, Q_{of} in equation 1 can be set to be a function of overflow pipe properties and downstream conditions (see **Roldin et al., 2012 – Paper I** for more details).

If several soakaways are aggregated and the K_{fs} parameters can be assumed to be lognormally distributed, the averaging method of Eq. 3 is proposed (**Roldin et al., 2012 – Paper I**):

$$K_{fs,effective} = \left(\prod_{i=1}^{n} K_{fs,i}{}^{L_i}\right)^{1/\sum_{i=1}^{n} L_i} \qquad \text{Eq.3}$$

where L_i is the length of soakaway i. For long simulation periods where clogging can be assumed to affect the infiltration rate, equation 4 is proposed to alter the value of K_{fs} during the simulated period (**Bergman et al., 2011 – Paper III**):

$$K_{fs,clogged}(t) = \frac{1}{\frac{1}{K_{fs,0}} + c \cdot t} \qquad \text{Eq.4}$$

where c is a fitting parameter that can either be calibrated or estimated from physical parameters (see **Bergman et al., 2011 – Paper III** for more details).

During dry weather periods where $Q_{in} = Q_{of} = 0$, the combination of Equation 1 and 2 has a simple analytical solution that can be used to estimate the initial water level in the soakaway at the next rainfall event. Equations 2-4 can be combined to suit the requirements and purpose of a specific simulation. However, the analytical solution for Equation 1 and Equation 2 is only valid for K_{fs} values that are constant with time, and if this equation should be used in combination with Equation 4 it is suggested that the $K_{fs,clogged}$ parameter is evaluated once at the start of a new wet-weather period, and is then kept constant until the next rainfall event.

3.7 Example from an application

The solution presented above was applied to a case study in Husum, a suburb in western Copenhagen, where it was determined whether soakaway infiltration can be used to reduce combined sewer overflows (**Roldin et al., 2012 – Paper IV**). Husum (Figure 10) is a 3 km2 residential area, with relatively high groundwater levels, low permeability soils and several contaminated sites, making stormwater infiltration challenging.

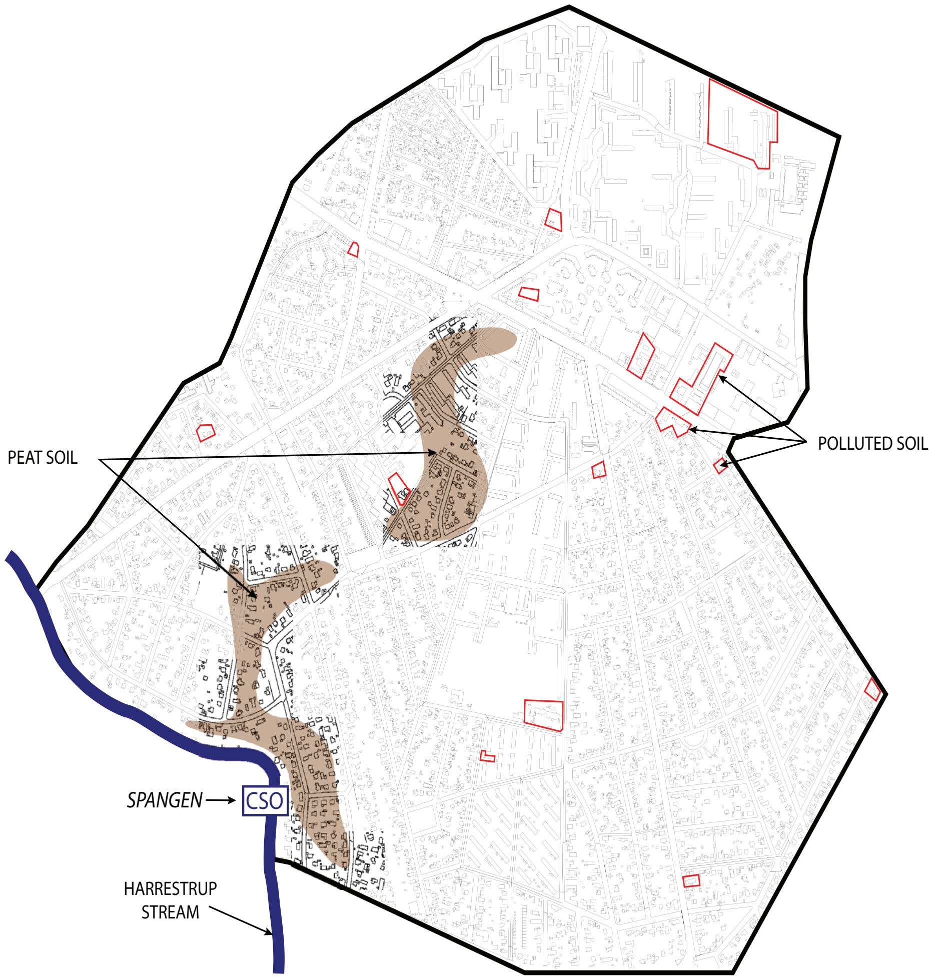

Figure 10. Map of the case study area. The main combined sewer overflow (CSO) structure, *SPANGEN*, is marked on the map, as well as polluted soil sites and areas with peat soil. From **Roldin et al. (2012 – Paper IV)**.

The soakaway model, based on Equation 1 and 2, was coupled to the distributed urban drainage model shown in Figure 7. Since the existing urban drainage model was set up at a scale larger than that of individual allotments, the upscaling principle described in Equation 3 was also employed. Runoff and pipe flow simulations were run with a 10-year rainfall series for three scenarios; a base scenario (current situation), a potential infiltration scenario (not restricted by groundwater conditions) and a realistic infiltration scenario where groundwater constraints were also considered. The two infiltration scenarios were modeled both by using the soakaway model coupled to the pipe flow model, and by using a simpler method where soakaway infiltration is represented by a reduction of the impervious area in the rainfall-runoff model. The potential infiltration scenario was also modeled with a lower K_{fs}-value to evaluate the sensitivity of the results to this parameter, as it is often highly uncertain.

The results, summarized in Figure 11, showed that groundwater constraints are important to consider, and that the hydraulic coupling between soakaways and pipe flow model can have a large impact on the results.

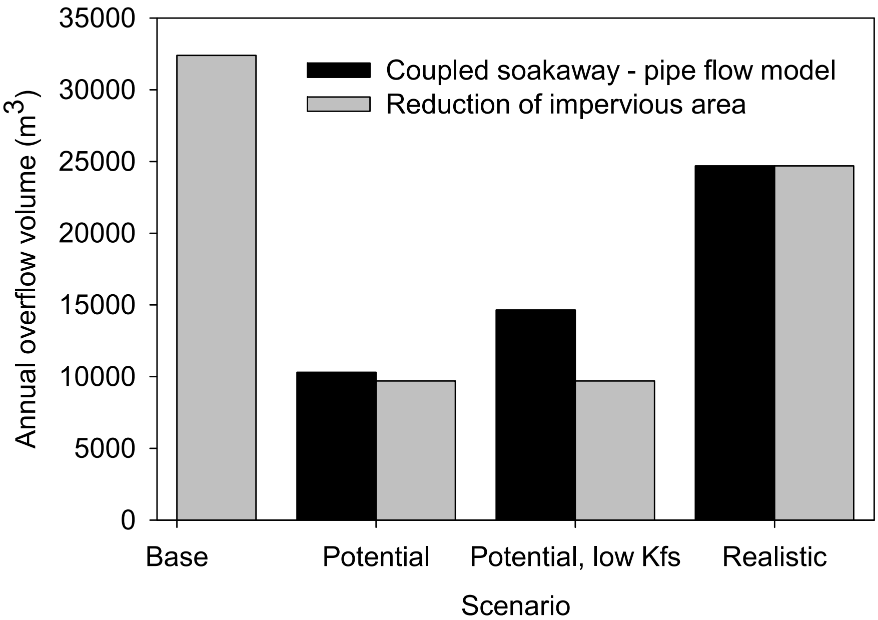

Figure 11. Modeled annual overflow volumes at the main combined sewer overflow structure in Husum for four different scenarios. Modified from **Roldin et al. (2012 – Paper IV)**.

The simulations in this study were performed using a decoupled approach to the groundwater simulations, where the effects on groundwater levels were first evaluated for several different infiltration scenarios, and then the results from the groundwater simulations used as an additional restriction on the amount of impervious area that could be connected to soakaways in the coupled soakaway – urban drainage model. Since the results show that groundwater constraints have a major impact on soakaway infiltration, it is particularly important that the interaction between infiltration and groundwater is adequately represented in the model. The following chapter describes various methods for representing soakaway infiltration in groundwater models, and presents a suggestion for how the bi-directional interaction between infiltration and groundwater can be modeled.

4. Modeling soakaways in distributed groundwater models

Distributed groundwater models are models which are able to simulate 2D or 3D groundwater flow with distributed data in a gridded system such as a finite difference grid or a finite element mesh. (e.g. Gustafsson et al., 1998; Jeppesen et al., 2011). Figure 12 shows a conceptual example of a distributed groundwater flow model with a finite difference grid.

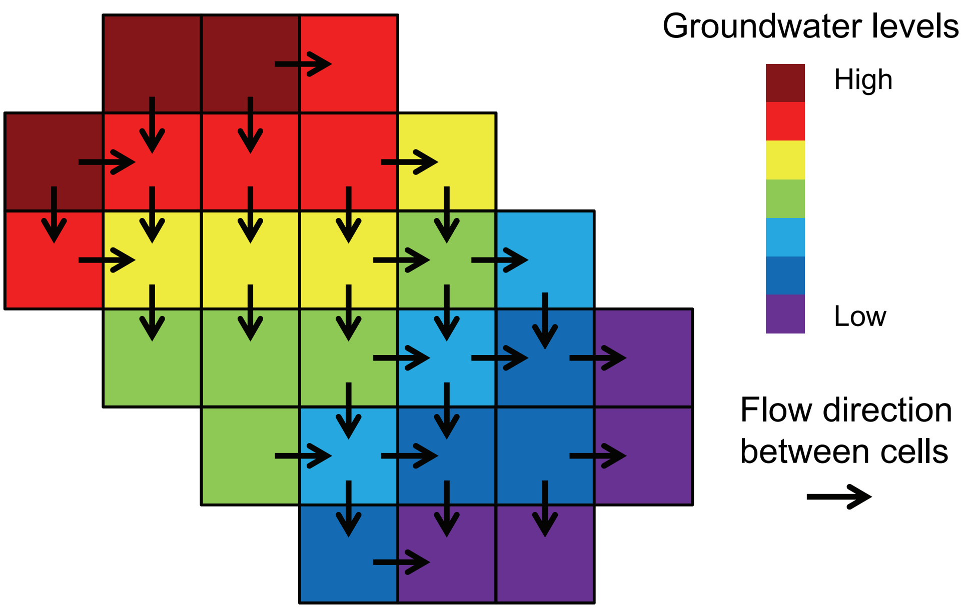

Figure 12. Conceptual illustration of a distributed groundwater flow model

4.1 Model complexity

Distributed, physically based groundwater models are computationally demanding, and thus an additional soakaway component should ideally be simple in order to add as little as possible to the computational effort. However, unlike urban drainage models, groundwater models generally include physically based and relatively complex methods for unsaturated and saturated flow (e.g. Richards' equation, Richards, 1931), and therefore it would be advantageous if the existing parameters and/or computations in the groundwater model can be re-used for the soakaway model. An example where parameters from an unsaturated/saturated flow model have been re-used in a relatively simple soakaway infiltration model is **Roldin et al. (2012 – paper II)**.

4.2 Infiltration flow pattern in the unsaturated zone

Infiltration equations and unsaturated zone models are often part of distributed groundwater models (Barlow and Harbaugh, 2006; DHI, 2011b) but they are generally 1-dimensional (vertical infiltration) since unsaturated flow modeling requires a lot of computational effort (see e.g. DHI, 2011b or **Roldin et al., 2012 – paper II**), and also since vertical infiltration is the dominant flow direction on a regional scale. 2-dimensional infiltration patterns from soakaways and how they affect the groundwater are found in literature, but these either consider individual soakaways on a very small scale (e.g. Guo, 1998) or they employ separate modeling systems for soakaway infiltration and groundwater flow, respectively (e.g. Göbel et al., 2004).

4.3 Spatial scale and resolution

To be able to model the bi-directional interaction between small-scale stormwater infiltration systems and a shallow groundwater table, including local mounding effects, the distributed groundwater model needs to be set up with a spatial resolution (grid size) similar to the size of the soakaway (e.g. Markussen et al., 2004; Maimone et al., 2011). However, distributed groundwater models for cities or larger regions are generally set up at a spatial scale much larger than the average soakaway size; the resolution may be of the order of magnitude 50-100 m or more (e.g. Vazquez et al., 2002; Jeppesen, 2010). So far, this problem has usually been solved with separate sequential simulations for soakway infiltration and groundwater flow (e.g. Göbel et al., 2004; Maimone et al., 2011**; Roldin et al., 2012 – paper IV**) due to the complexity of the interactions and the difficulties of overcoming the variety of spatial scales in the involved models. Bi-directional simulations have been made on city scale, where the focus has been on evaluating the effect of massive stormwater infiltration on regional groundwater levels, and local mounding effects have thus been omitted (Jeppesen, 2010).

In **Roldin et al. (2012 – paper II)**, an alternative solution is presented where a soakway infiltration model is used in combination with a downscaling method to estimate the local mound from a regional groundwater level (e.g. the water level in a regional scale groundwater model). This method allows bi-directional interaction determining the effect of soakaways on both infiltration rates and local groundwater levels, without requiring a very fine spatial resolution for the groundwater model. A conceptual illustration is shown in Figure 13.

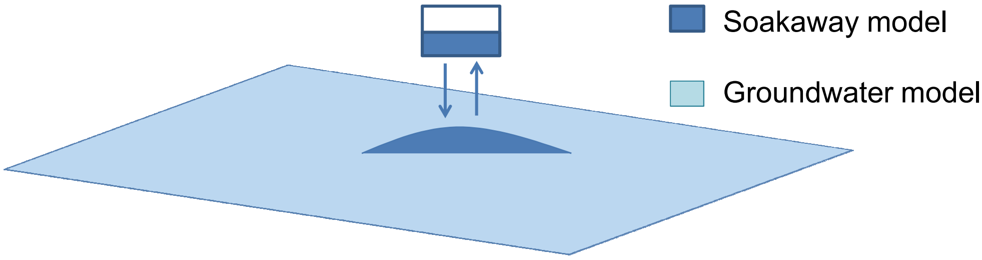

Figure 13. Conceptual illustration of the soakaway infiltration model and local mounding model coupled to a distributed groundwater model (only one grid cell of the groundwater model is shown). Based on the model described in **Roldin et al. (2012 – Paper II)**.

It is also important to consider the spatial scale of interaction between multiple soakaways and possible aggregation methods to avoid having to model individual soakaways in large catchments. Interconnected mounds and flow between individual soakaways has been examined in literature (e.g. Antia, 2008), but aggregation methods for soakaways in distributed groundwater models is a field for future research.

4.4 Temporal scale and resolution

Infiltration processes have a similar time scale to groundwater flow; however the response time is related to the spatial scale of the modeled phenomenon – a city-scale groundwater model may be run with a time step of 24 h (e.g. Jeppesen et al., 2011) but this will be inadequate for a model with a fine spatial resolution (e.g. **Roldin et al., 2012 – paper II**). If a soakaway model component including local mounding effects is coupled to a groundwater model (as described in 4.3) it is therefore likely that the soakaway model needs to be run with a higher temporal resolution than the groundwater model.

Furthermore, if the coupled soakaway-groundwater model is also coupled to an urban drainage model and used to analyze effects on sewer flows, it should preferably have a temporal resolution of the same order of magnitude as the runoff hydrographs in the urban drainage model, which can be in the range of minutes (Elliott and Trowsdale, 2007).

4.5 Integration with groundwater models

Coupled soakaway – analytical groundwater models are available for single or few soakaways (e.g. Guo, 1998; Korkmaz and Önder, 2006). Soakaways and numerical distributed groundwater models have been coupled on small catchments with high spatial resolution (e.g Markussen et al., 2004; Maimone et al., 2011). For larger catchments, existing modeling studies are either not bi-directional (e.g. **Roldin et al., 2012 – Paper IV**) or are not suited for modeling small-scale structures and local effects (e.g. Jeppesen, 2010). Since the interaction between soakaway infiltration and groundwater mound is known to be bi-directional (e.g. Bouwer, 2002; **Roldin et al., 2012 – Paper II**), a bi-directional modeling approach is likely to be more accurate.

Soakaways are located above the groundwater table and the infiltration outflow from a soakaway will first be added to the unsaturated zone before eventually recharging the groundwater. When integrating a soakaway model with a groundwater and unsaturated zone model, the most realistic approach would thus be to model the infiltration as part of the unsaturated zone flow. However, unsaturated flow modeling is more complex than saturated flow modeling, and the advantages of this approach must thus be weighed against possible disadvantages such as additional computational effort.

Finally, if the coupled soakaway-groundwater model is to be used with a distributed urban drainage model, the selected model type and integration method should also be compatible with the solution presented in section 3.6. The OpenMI framework (Gregersen et al., 2007) is therefore well suited to use to create the connections, since it can be used in combination with any model that is OpenMI compliant, and offers a large flexibility in terms of how differences in spatial and temporal scales between models are handled. An OpenMI-compliant soakaway module has been developed during the course of this PhD study, but it has not yet been tested in any practical applications.

4.6 Suggested solutions

This chapter shows that a soakaway model coupled to a distributed groundwater model should preferably fulfill the following criteria:

- Require little computational effort.
- Be based on soil data usually available in a groundwater model to avoid extra calibration.
- Be able to account for the bi-directional interaction between soakaway infiltration and local groundwater mounding.

- Be possible to use in distributed groundwater models with coarser spatial resolution than the mound extent, i.e. include a downscaling technique to account for the mound.
- Be possible to run with another temporal resolution than the groundwater model.
- Be compatible with the soakaway model proposed for distributed urban drainage models.

A model that meets all the above requirements is presented in **Roldin et al., 2012 – paper II**. The basic concept is that the infiltration rate is related to the soil moisture retention curve $\theta(h)$ and the distance to the local groundwater level below the soakaway, according to Equation 5:

$$Q_{inf,grw} = \frac{\theta_s - \theta(\Delta h)}{\theta_s - \theta_i} Q_{inf,0} \qquad \text{Eq.5}$$

$Q_{inf,grw}$ is the infiltration rate influenced by groundwater, $Q_{inf,0}$ is the infiltration rate that would be if there was no mounding effect (equal to Equation 2 in section 3.6), Δh is the distance between the soakaway bottom and the local groundwater level below the soakaway (i.e. the top of the groundwater mound). The local mounding depth is calculated using a known analytical solution for groundwater mounds (Hantush, 1967) using knowledge of infiltration rate and regional groundwater level. This is a form of downscaling technique for groundwater levels which makes the soakaway model possible to use with distributed groundwater models regardless of the spatial resolution. Figure 14 shows the soakaway water level results of a modeling study with a 2D unsaturated/saturated flow model, Equation 5 (with groundwater interference) and Equation 2 (no groundwater interference).

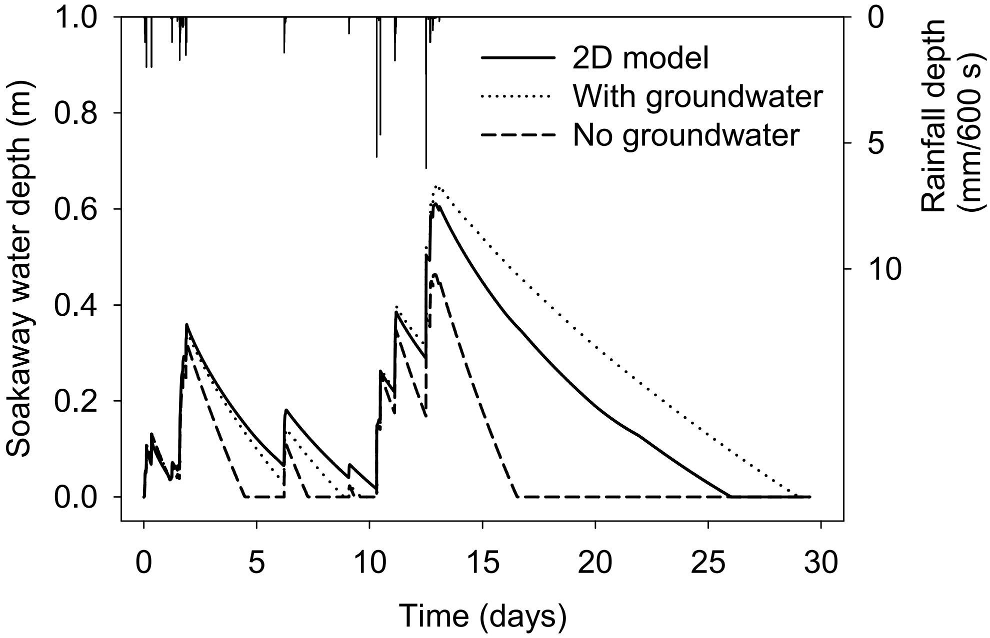

Figure 14. Soakaway water level results from a modeling study with a 2D model (solid black line), the simplified model with groundwater interaction applied (dotted line), and the simplified model without groundwater interaction (dashed line). See **Roldin et al., 2012 – Paper II**.

The infiltrated water is added to the saturated zone after a lag time, which represents the travel time through the unsaturated zone. The presented solution can thus be used with a groundwater flow model regardless of whether the latter contains an unsaturated flow component or not.

The model in Equation 5 is can be combined with the equations for soakaways presented in 3.6. However, it should be noted that aggregation of several soakaways and their effect on groundwater has not been investigated in **Roldin et al. (2012 – Paper II)**. Upscaling or aggregation methods and the interaction between multiple soakaways need to be investigated before Equation 5 can be used for multiple soakaways.

5. Discussion and perspectives

To assess the value of the model solution presented in chapter 3 and 4 and in **Roldin et al. (2012 – Paper I - II)** and **Bergman et al. (2011 – Paper III)**, the experiences gained from practical applications with the model are discussed, and the solution is compared with a similar approach from the literature. Potential future applications and developments of the proposed modeling concept are also discussed in this chapter.

5.1 Experiences gained from practical applications

The field studies where the proposed model has been applied, show that the modeling concept, although it is relatively simple, can represent soakaway dynamics sufficiently well (**Roldin et al., 2012 – Paper I**) and that clogging is likely to have a substantial effect on the overflow volumes and frequency from the soakaway to the sewer system (**Bergman et al., 2011 – Paper III**) for which reason it is therefore important to include in long term simulations.

The model has also been used in case studies to estimate and predict the effects of various soakaway scenarios on sewer and groundwater flows. The case studies indicate that the upscaling/aggregation of individual soakaways in an urban drainage model will have a minor effect on the results (**Roldin et al., 2012 – Paper I**), that the hydraulic coupling between soakaways and sewers is important to include in the model (**Roldin et al., 2012 – paper IV**) and that shallow groundwater tables and low conductivity soils are very important to account for in order to assess the effectiveness of soakaways (ibid.). The experiences gained from these field studies and case studies emphasize the need for an integrated modeling approach and confirm that the suggested model can be a useful tool in practical applications.

5.2 Comparison with an alternative approach.

One of few other existing modeling concepts that couples distributed models of soakaways, urban drainage and groundwater is presented by Jeppesen (2010), which considered the same study area as this thesis.

The work presented in this thesis largely considered individual soakaway behavior, focusing on interactions on a small spatial and temporal scale, e.g. local mounding effects and analyses of water flows during individual rainfall events. The models can be directly coupled to a pipe flow model, where their relatively small temporal and spatial scale make them particularly suited for the evaluation of the impacts on sewer flows. The models can also be used to estimate groundwater recharge and annual water balances, but this is not their primary intention.

In contrast, Jeppesen's (2010) model considers a larger spatial scale and its main focus is on how the (regional) groundwater level is affected by massive infiltration from soakaways, and how this water level affects the soakaway performance, in particular situations where groundwater starts draining into the soakaway. A sewer component is included as a part of the groundwater model to quantify recharge to groundwater from leaking sewers and infiltration of groundwater to sewers. The focus on groundwater rather than urban drainage, and the large spatial and temporal scale, means that Jeppesen's model is ideally suited for the estimation of annual water budgets and long term effects of infiltration on the groundwater levels in a city. However, Jeppesen's model is less suited for the detailed analysis sewer flows and the effects of single rainfall events on the urban water system.

Both the large scale approach of Jeppesen and that of this thesis are need to quantify urban water flows, and it would be interesting to see if and how these two modeling approaches could be combined so as to benefit from the advantages of both methods.

5.3 Potential future applications and model developments

The presented model is intended for use in distributed modeling studies on the effect of soakaway infiltration on urban drainage systems and/or groundwater. The model can be used for both event-based and long-term studies, and is suited for detailed studies on small catchments as well as for estimating impacts on larger catchments.

An application was used to illustrate how the soakaway model can be coupled to an urban drainage model and used to estimate the effects of soakaway infiltration on combined sewage overflows. A future case study could couple the soakaway model to an urban drainage – 2D overland flow model (e.g. Leandro et al., 2009) to assess the effectiveness of soakaway infiltration on alleviating urban flooding during extreme events.

Soakaways are not the only WSUD option for stormwater infiltration and runoff reduction. Alternative techniques such as rain gardens, swales, permeable pavements and green roofs (Revitt et al., 2003) can also be employed, and future work could include the development of other new models which consider other types of WSUD systems. Many of these systems also aim to improve water quality, and extending the models to consider water quality is also important future work.

In summary, there is a wide range of possible applications of the current modeling concept, and also good potential for the further development and improvement of the model to increase its usefulness. To facilitate the application of the model it should be implemented as an OpenMIcompliant component (Gregersen et al., 2007) so as to enable coupling to existing commercial urban drainage and groundwater models.

6. Conclusions

Soakaway infiltration can be modeled with distributed urban drainage and groundwater models by using a base equation (Equation 2), which can be supplemented with one or several additional components depending on the need and purpose. The suggested solution is illustrated graphically in Figure 15.

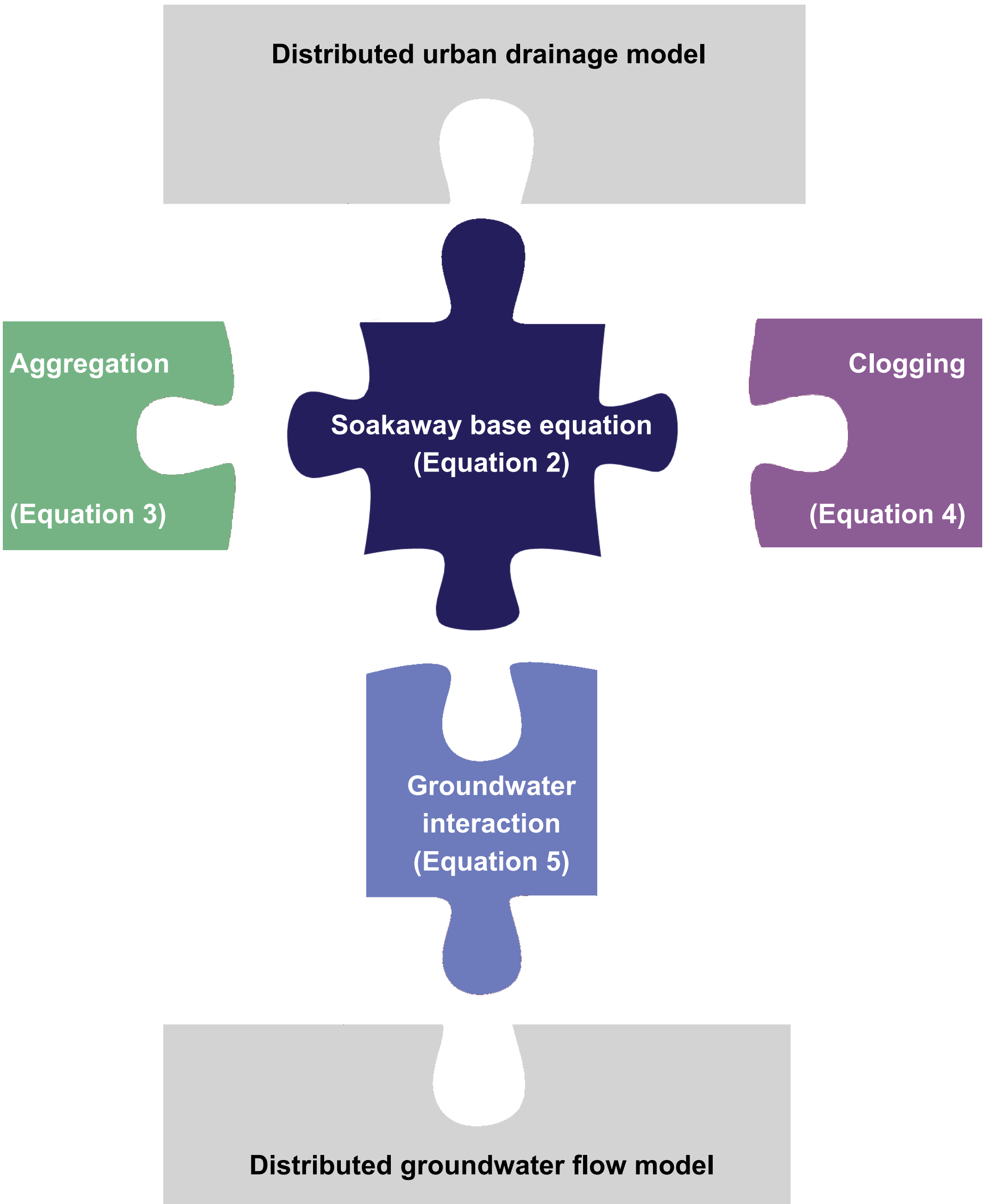

Figure 15. Conceptual illustration of the suggested modeling concept

The advantages of the modeling concept in Figure 15 are that it is

- flexible – additional components for clogging, aggregation of multiple soakaways and groundwater interference can be added and combined depending on the need for the specific simulation
- simple to use – it requires no calibration and is based on physical parameters that are usually part of urban drainage and groundwater models
- efficient – it requires little extra computational effort and is substantially faster than corresponding 2D models
- reasonably accurate – studies show that the error introduced by the simplifications are marginal compared to other sources of uncertainty

In short, the modeling concept can be used for a range of various situations, and applications shown in the thesis demonstrate that the advantages of the suggested model outweigh the disadvantages arising from the extra uncertainty introduced by the simplifications.

This modeling concept has addressed the objectives outlined in section 1.5. An appropriate model type for modeling soakaways in distributed models has been selected (Objective 1), and a model that considers the bi-directional interaction between infiltration and groundwater has been presented (Objective 2). Upscaling and downscaling techniques have been developed and tested (Objective 3), however upscaling/aggregation methods for multiple soakaway in groundwater models remains a topic for future research. The effect of extensive soakaway implementation on sewer flows was evaluated for a case study (Objective 4). While the models developed in this thesis can estimate the impact of soakaway infiltration on groundwater levels, the fully coupled soakaway/groundwater model was not employed for the case study because of time limitations and the need for further investigation of upscaling methods, including the interaction between multiple soakaways.

7. Recommendations

When research is presented to answer a scientific question, the results will inevitably give rise to further questions and point out new interesting fields of research. Based on the discussions and conclusions presented in this thesis, supplementary research is recommended within the following fields:

- **Multiple soakaway modeling coupled to distributed groundwater models.**
  This topic includes interaction effects between closely spaced soakaways such as interconnected mounds and flow between soakaways, as well as upscaling/aggregation methods for individual soakaways and estimates of the error introduced by aggregation. Studies on this topic are necessary to be able to use the presented soakaway model and groundwater coupling component in an applied context with more than one soakaway. It is therefore strongly recommended that further research be conducted on interaction between individual soakaways and aggregation methods for soakaways in distributed groundwater models, before multiple soakaway modeling is used for practical applications in a distributed groundwater model.

- **Integrated case studies with simultaneous urban drainage, soakaway and groundwater modeling**
  The coupling of the new model to a distributed urban drainage model has been evaluated in this thesis for a case study, but the groundwater coupling has only been evaluated for a theoretical modeling study. It is recommended that a case study be carried out where the proposed soakaway model is coupled both to a distributed urban drainage model and a distributed groundwater model.

- **Other WSUD techniques**
  Soakaways are just one of many existing WSUD techniques, and a modeling concept involving other kinds of commonly found WSUD systems would therefore be much more useful than a model for soakaways only. Suggested structures to incorporate in a WSUD model are e.g. green roofs, permeable pavements and swales.

- **Water quality modeling**

  Many WSUD techniques are primarily aimed at improving the stormwater quality, and less focused on reducing runoff volumes. In an extended model with various kinds of WSUD structures, it is therefore recommended that water quality also be a part of the model.

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9. Papers

I. **Roldin, M.**, Mark, O., Kuczera, G., Mikkelsen, P.S. and Binning, P.J. (2012). *Representing soakaways in a physically distributed urban drainage model – upscaling invidiual allotments to an aggregated scale*. Journal of Hydrology, 414-415, 530-538.

II. **Roldin, M.**, Mark, O., Mikkelsen, P.S. and Binning, P.J. (submitted) *A simplified model for soakaway infiltration interaction with a shallow groundwater table.* Submitted.

III. **Bergman, M.**, Hedegaard, M. R., Petersen, M.F., Binning, P., Mark, O. and Mikkelsen, P.S. (2011). *Evaluation of two stormwater infiltration trenches in central Copenhagen after 15 years of operation.* Water Science and Technology 63(10), 2279-2286.

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DTU Environment
Department of Environmental Engineering
Technical University of Denmark

Miljoevej, building 113
DK-2800 Kgs. Lyngby
Denmark

Phone: +45 4525 1600
Fax: +45 4593 2850
e-mail: reception@env.dtu.dk
www.env.dtu.dk

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